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DRAG AND STABILITY OF CROSS TYPE PARACHUTES

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UNIVERSITY OF MINNESOTA

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FOREWORD

This report was prepared by the Department of Aeronautics and Engineering Mechanics of the University of Minnesota in compliance with AF Contract No. AF33(657)-11184, Project No. 6065 and Task No. 606503. The work being accomplished under this contract is sponsored jointly by U. S. Army Natick Laboratory, Department of the Army; Bureau of Aeronautics and Bureau of Ordnance, Department of the Navy; and Air Force Systems Command, Department of the Air Force, and is directed by a Tri-Service Steering Committee concerned with Aerodynamic Retardation. Contract administration has been conducted by the Research and Technology Division (AFSC), and Messrs. Rudi J. Berndt and James H. DeWeese of the Recovery and Crew Station Branch, AF Flight Dynamics Laboratory, have been project engineers.

This study was accomplished under the direction of Prof. H. G. Heinrich. Several graduate and undergraduate students in aerospace engineering participated in the performance of the experiments and data evaluation. The authors wish to express their appreciation to them.

This technical documentary report has been reviewed and is approved.

THERON J. BAKER
Vehicle Equipment Division
AF Flight Dynamics Laboratory

ABSTRACT

Wind tunnel studies have been performed on several configurations of the Cross parachute. Both the canopy geometry and the cloth porosity have been varied to provide data over the entire range for which the canopy may be used. In addition, the performance of these canopies in the wake of a forebody has been evaluated.

This report contains the results of three-component studies on these models as well as a discussion of the canopy performance in light of the tests performed.

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ILLUSTRATIONS

ILLUSTRATIONS (cont.)

TABLES

SYMBOLS

A	frontal area of forebody
b	maximum frontal dimension of forebody
C	effective porosity
C_M	moment coefficient
C_N	normal force coefficient
C_T	tangent force coefficient
D_o	nominal diameter based on S_o
d	total inflated model length
h	inflated canopy depth
k	moment arm
L	canopy panel length
l	suspension line length
M	moment
N	normal force
q	dynamic pressure $= \frac{1}{2}\rho V^2$
S_o	essential canopy area (no overlapping)
T	tangent force
U	average velocity through parachute cloth
V	velocity
W	canopy panel width
α	angle of attack
ρ	air density
λ	geometric porosity

1. INTRODUCTION

The Cross parachute has demonstrated a high degree of stability as well as satisfactory drag characteristics in full scale drop tests. Its use as a cargo parachute is further enhanced by the apparent ease and economy of fabrication.

In an effort to evaluate the performance of this type of canopy under laboratory conditions, and further, to determine a possible optimum configuration, the University of Minnesota has performed a series of wind tunnel studies on several Cross type canopy designs both in free stream and in the wake of simulated cargo containers.

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2. EXPERIMENTAL PROCEDURE

A. Coordinate System and Coefficients

The parachute coordinate system (Fig 1) uses the physical coordinates of the parachute as the major reference axes. The pertinent forces and moments are the following:

a) The tangent force, T, acting along the centerline of the parachute;

b) The normal force, N, acting perpendicular to the parachute centerline;

c) The moment, M, is defined as the aerodynamic moment about a moment center located one parachute nominal diameter, D_o, upstream from the skirt of the canopy. This is considered a stabilizing moment when the slope of the curve, $\frac{dC_M}{d\alpha} < 0$. (Ref 1).

The force and moment coefficients were calculated from test data and employ the conventional aerodynamic relationships, where $C_{T_o} = \frac{T}{qS_o}$, $C_{N_o} = \frac{N}{qS_o}$ and $C_{M_o} = \frac{M}{qS_oD_o}$. In Ref 1 it is shown that the relationship M = Nk may be used.

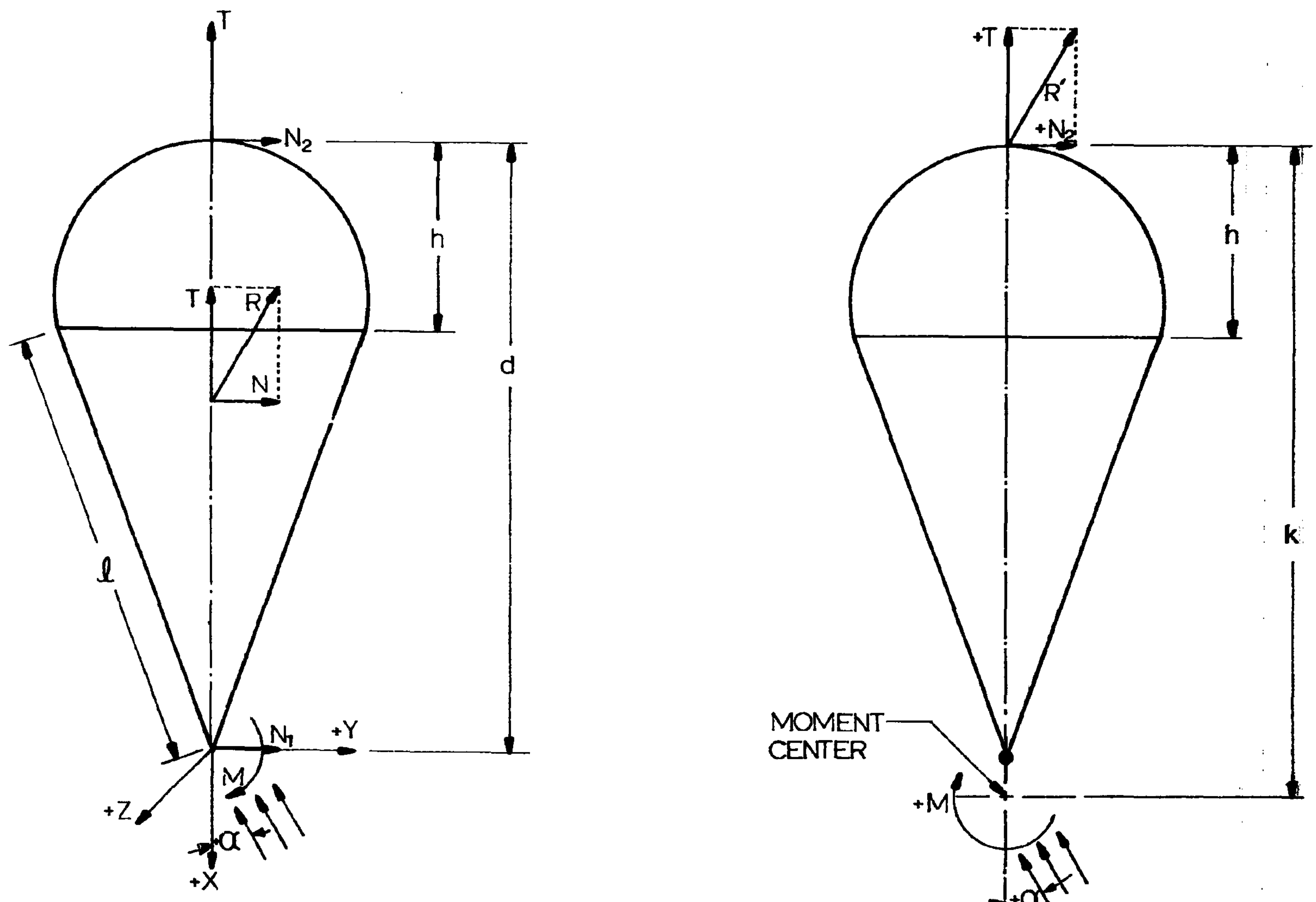
The nominal diameter, used in determining the moment coefficients for the Cross parachute models, is defined as:

$$D_o = \sqrt{\frac{4\ S_o}{\pi}} ,$$

where S_o is the essential cloth area (ie. no overlapping) of the canopy panels.

B. Models

Design data for the orginal 18 foot diameter Cross type configuration was supplied by the Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. The model of this canopy was constructed of two panels each having a width to length ratio (W/L) of 0.264, sewn together perpendicular



A). GENERAL SYSTEM

B). WIND TUNNEL SYSTEM (NEGLECTING N_1)

FIG 1. PARACHUTE COORDINATE SYSTEM AND FORCES

to each other (Fig 2). Four canopy models were constructed with this W/L configuration, having porosities shown in Table 1. This tabulation also shows the pertinent data for two other W/L configurations with various cloth porosities.

The nominal porosity range of the parachute materials used in this investigation and presented in Table 1 represents a volumetric flow in units of ft^3/ft^2 -min at $\frac{1}{2}$ inch H_2O differential pressure.

A second cloth parameter, to which later reference will be made, is the effective porosity of the material. This is defined as the ratio of the average velocity, U, through the porous cloth surface to a fictitious free stream velocity, V, defined by the differential pressure across the cloth (Ref 2). By the method outlined in Ref 2 the effective porosities of the cloth materials used were measured at the same density ratio and differential pressure existing in the wind tunnel tests.

The geometric porosity shown in Table 1 is obtained by circumscribing a circle with a diameter equal to the panel length, L, around the canopy. The ratio of the open area to the total area of this disk is defined as the geometric porosity.

Each parachute model has a panel length, L, of 18 inches and 20 suspension lines each 18 inches in length of 100 lb nylon cord. A total of ten models were tested in free stream and three of these were selected for further examination in the wake of a forebody.

Two A-21 cargo container models were used for the wake experiments. The dimensions of the container models, in view of the existing parachute models, were determined as follows. The A-21 cargo container is designed for loads ranging from approximately 100 to 500 lbs (Ref 3). Using average free stream tangent force coefficient values and assuming an equilibrium velocity of 25 ft/sec, the necessary

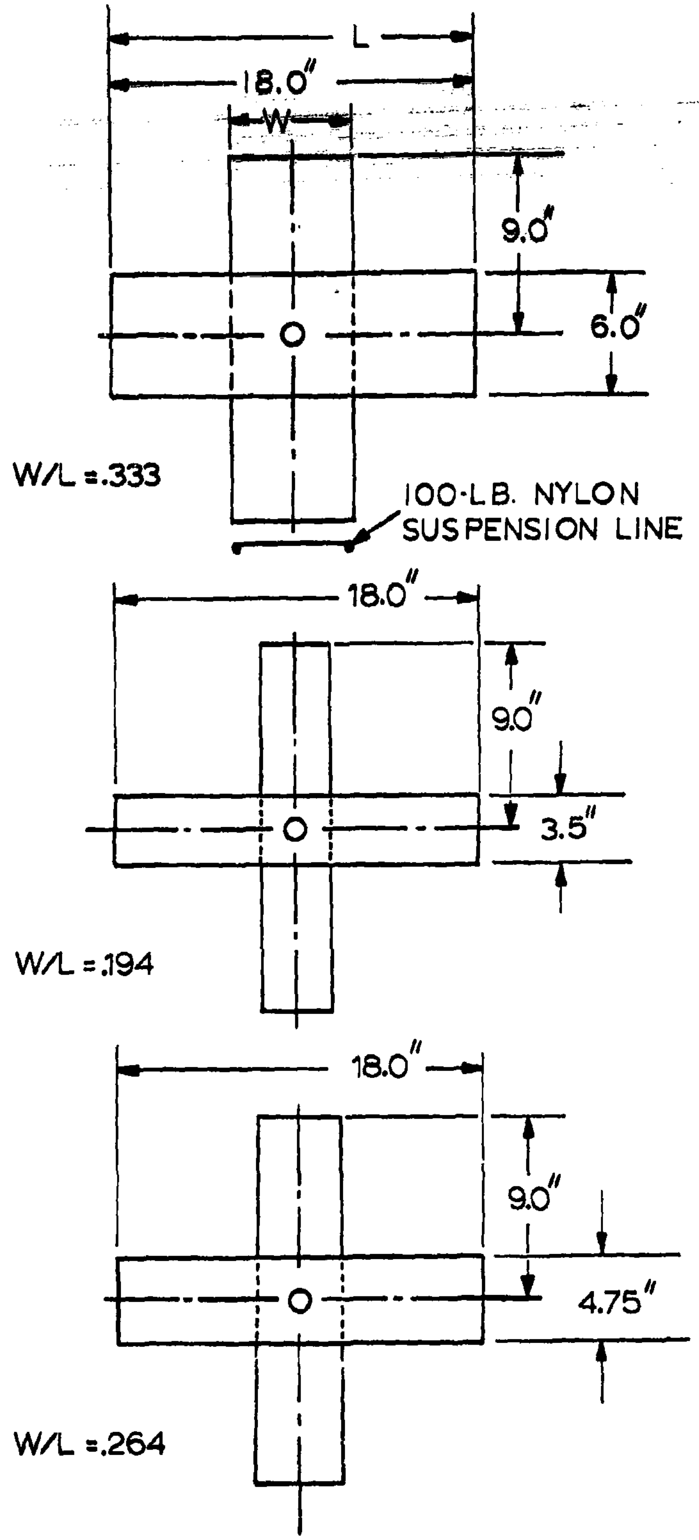


FIG 2. CROSS TYPE PARACHUTE MODEL CONFIGURATIONS

TABLE 1 DESIGN CHARACTERISTICS OF CROSS PARACHUTE MODELS

WIDTH W (in.)	$\frac{W}{L}$ (L = 18")	ESSENTIAL CLOTH AREA S_o (ft^2)	NOMINAL DIAMETER D_o (ft)	MOMENT ARM K (ft)	GEOMETRIC POROSITY λ	NOMINAL POROSITY	CLOTH SPECIFICATION (MIL-C No.)
6.00	.333	1.25	1.26	1.96 2.00 2.02	29.3%	9 - 11 60 - 90 120	107470 - D 8021 A -- I 7020B-- I
4.75	.264	1.03	1.16	1.94 1.96 1.98 1.98	41.7%	9 - 11 60 - 90 12C 194	107470 - D 8021 A -- I 7020 B -- I COTTON PRINT
3.50	.194	.79	1.00	1.98 1.94 2.00	55.3%	9 - 11 60 - 90 120	107470 - D 8021 A -- I 7020 B -- I

canopy area, S_0, was calculated.

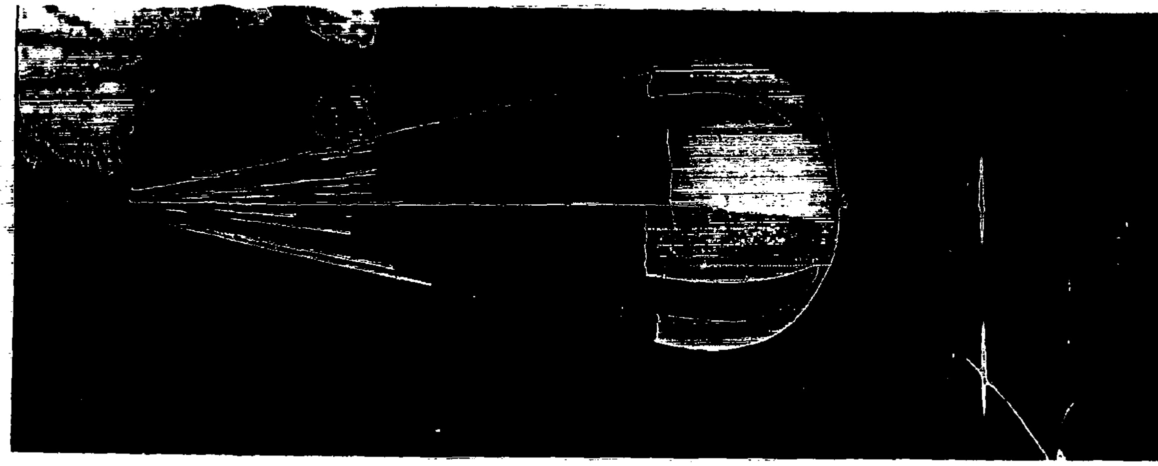
Calculations were made for container weights of 100 lbs and 500 lbs and the resulting scale factors for the container were derived to 1:12 and 1:30 for the 100 lb and 500 lb loads, respectively. Consequently, a parachute model which is combined with a simulated 100 lb container has a larger forebody than the same parachute model will have when combined with a 500 lb model container.

Forebody sizes relative to canopy panel length are $b/L = .278$ and $b/L = .112$ for the 100 lb and 500 lb loads, respectively, where b is the maximum dimension of the container, 60 inches full size. As a parameter, forebody size may be related to parachute size by the ratio A/S_0, where A is the frontal area of the forebody, 60" x 40" full scale. These area ratios of the various canopy-container combinations are presented in Table 3.

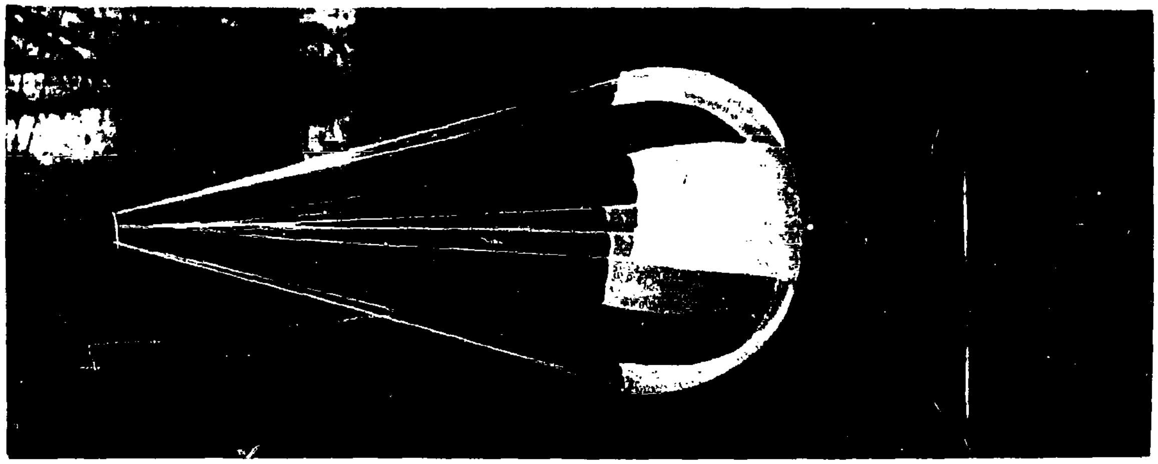
C. Test Arrangement and Procedure

Experiments were conducted in a horizontal return, atmospheric pressure wind tunnel with a test section of 38" x 54". Models were suspended on a turntable which was revolved to obtain different angles of attack. Force measurements were taken at 5° increments for large angles and $2\frac{1}{2}$° increments for angles of attack near zero. Normal and tangent force measurements were made by a strain gage balance and electronic recording system. Details of the method of force measurement and the force recording system are presented in Ref 1. Figure 3 shows three inflated models in the wind tunnel. Schematic drawings of the suspension system, and of the devices used to measure normal and tangent forces, are shown in Figs 4 and 5, respectively.

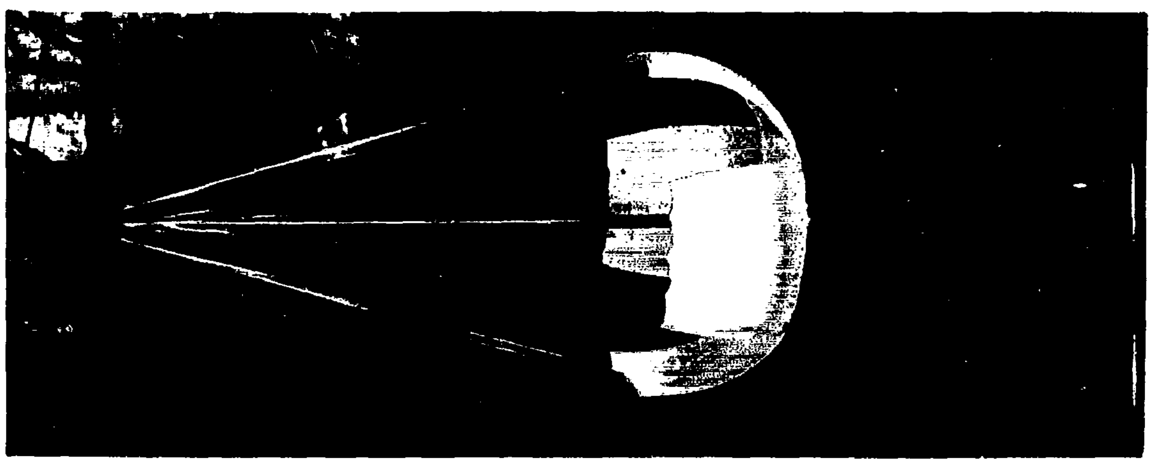
The test arrangements and procedure for the investigation of the Cross parachute in the wake of an A-21 forebody were basically the same as above. The only modification required



W/L = .194



W/L = .264



W/L = .333

FIG. 3 INFLATED PARACHUTE MODELS IN WIND TUNNEL

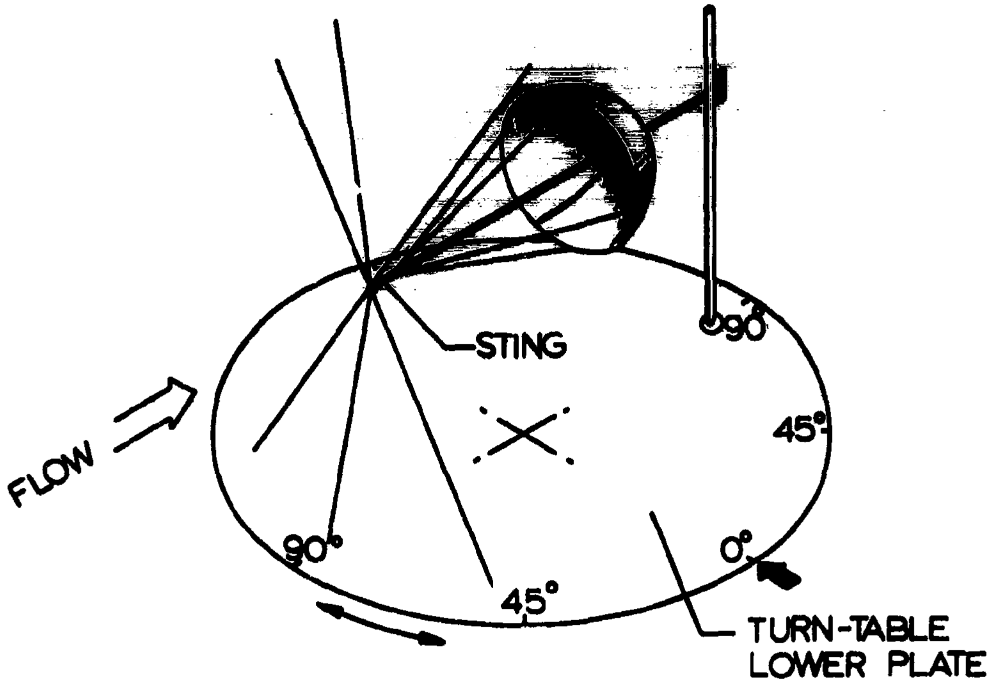


FIG 4. MODEL SUSPENSION SYSTEM

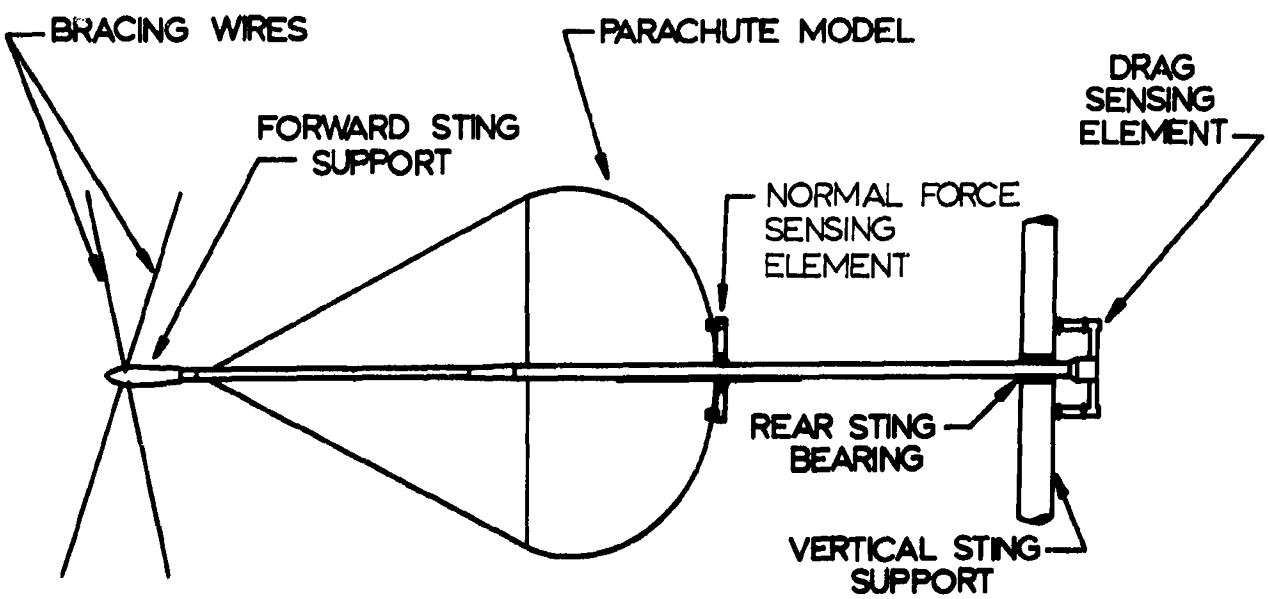


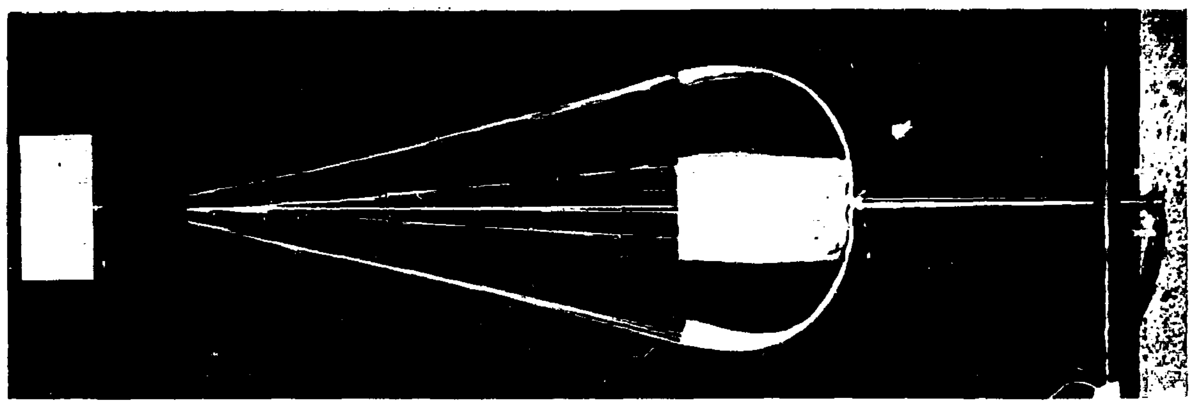
FIG 5. MODEL SUSPENSION AND STRAIN GAGE BALANCE ARRANGEMENT

is the mounting of the forebody by means of a sting extension which simulates the riser length.

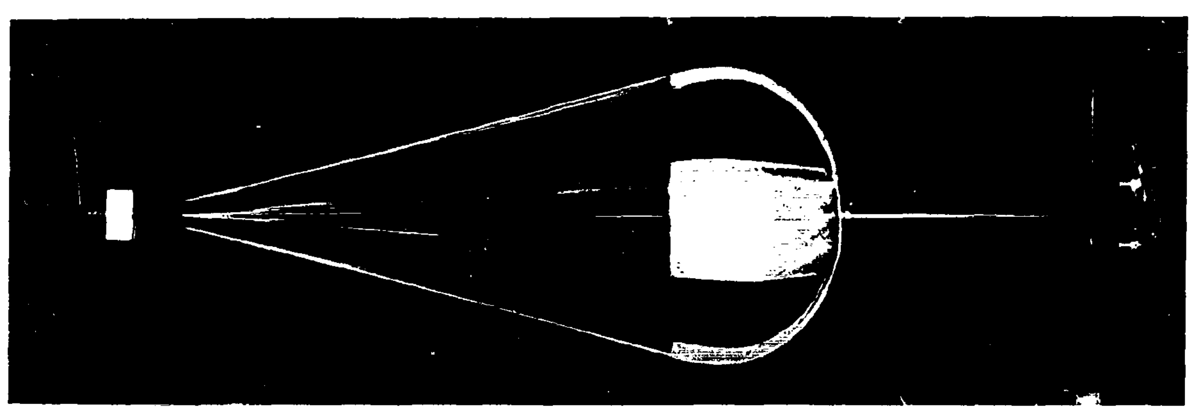
Three riser length - forebody combinations were used in the tests (Fig 6). The 1/12 scale A-21 forebody, representing a 100 lb load, was tested with a riser length of .80L, simulating a riser approximately equal to the nominal diameters of the parachutes tested. This same forebody was also tested with a riser length of .14L, representing a standard 30 inch cargo parachute riser (Ref 4). The 1/30 scale A-21 forebody, representing the 500 lb load, was tested with a riser length of .06L, again representing a standard riser. Each test arrangement was designed so that only those forces acting on the parachute were measured, the forces on the forebody being absorbed by the forward sting support.

All experiments were conducted at a free stream velocity of 66 ft/sec, corresponding to a Reynolds number, based on nominal diameter, of approximately 4.5×10^5. Tests were repeated several times on each model to assure reliable results.

b/L=.278 AND .80L RISER



b/L=.278 AND .14L RISER



b/L=.112 AND .06L RISER

FIG. 6 MOUNTING SYSTEM OF A-21 FOREBODIES WITH SIMULATED RISER LENGTHS

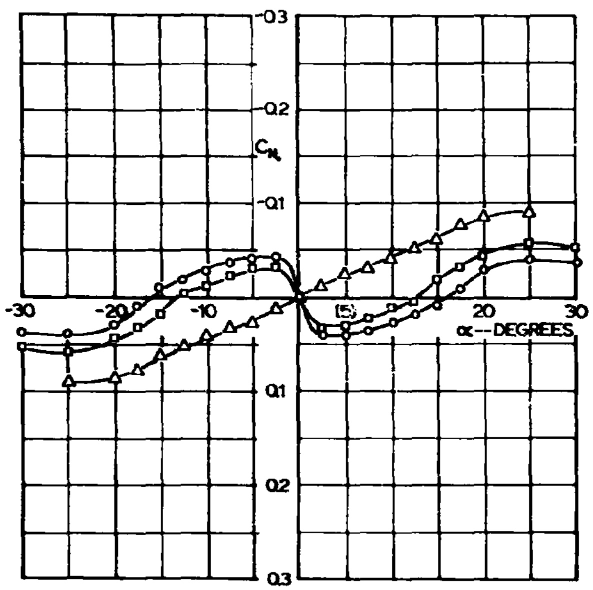
3. RESULTS AND CONCLUSIONS

A. Aerodynamic Characteristics of Cross Parachutes Singly Suspended

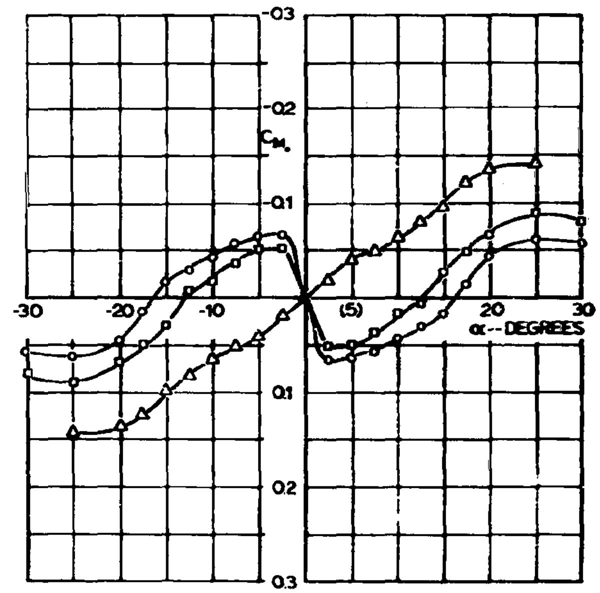
The aerodynamic coefficients of the models tested are presented in Figs 7, 8 and 9 as a function of angle of attack. The tangent force coefficient decreases as expected with increasing nominal and geometric porosity. In particular, the Cross parachute with a geometric porosity of 29.3% is stable only when built out of high porosity cloth (Fig 7).

The stability derivative, $\frac{\partial C_M}{\partial \alpha})_{\alpha = 0}$, decreases with increasing effective porosity for configurations with W/L = 0.333 but increases for configurations with W/L = 0.194 (Fig 10). The intermediate configuration, W/L = 0.264, appears to represent a transition region in the stability trend, since stability changes only slightly with effective porosity. This indicates that the canopy stability is a function of geometric porosity or inflated canopy shape, as well as of cloth porosity.

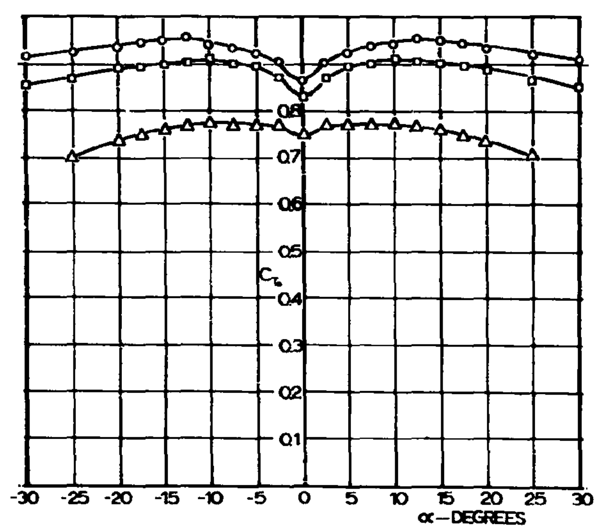
A graph of the stability derivative, $\frac{\partial C_M}{\partial \alpha})_{\alpha = 0}$, as a function of geometric porosity (based on a disk of diameter L) (Fig 11) for constant cloth porosities shows that the curves for various effective porosities have a common point of intersection at approximately 44% geometric porosity. For the geometric porosity range lower than 44 per cent, the parachutes behave in the conventional manner, with the canopies having more porous cloth demonstrating higher stability characteristics. However, Cross parachutes with a geometric porosity larger than 44 per cent show a lesser degree of stability as the cloth porosity increases. Results of free stream studies are summarized in Table 2.



NORMAL FORCE COEFFICIENT



MOMENT COEFFICIENT

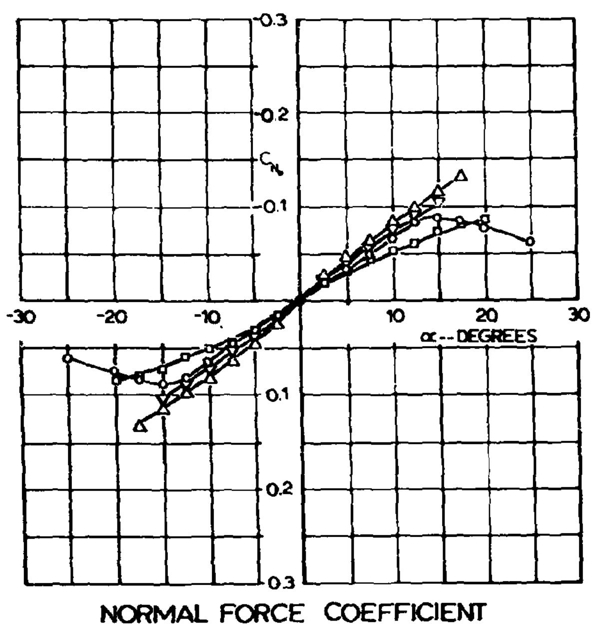


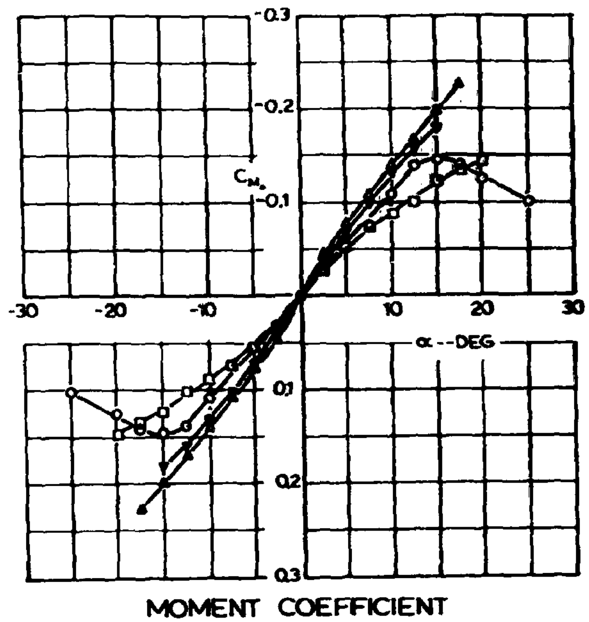
TANGENT FORCE COEFFICIENT

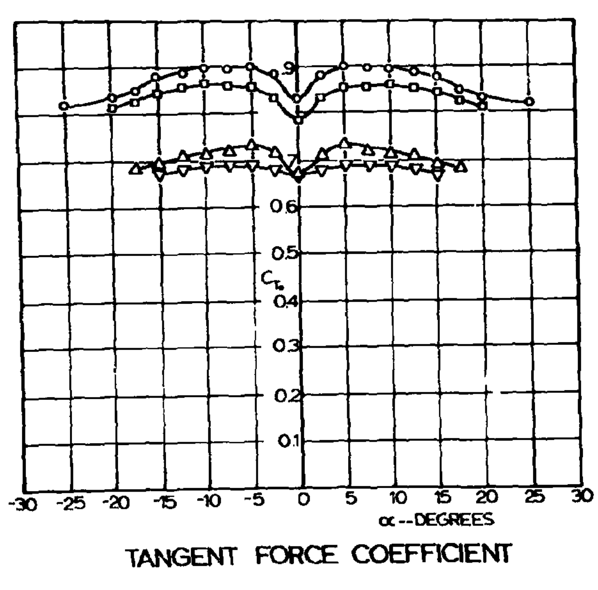
SYMBOL	NOMINAL POROSITY
o	9-11
□	60-90
Δ	120

FIG-7 AERODYNAMIC COEFFICIENTS vs ANGLE OF ATTACK FOR CROSS TYPE PARACHUTES OF VARIOUS NOMINAL POROSITIES (W/L=333, GEOMETRIC POROSITY 29.3%)

BASED ON S_o AND REYNOLDS NO. = 4.5×10^5

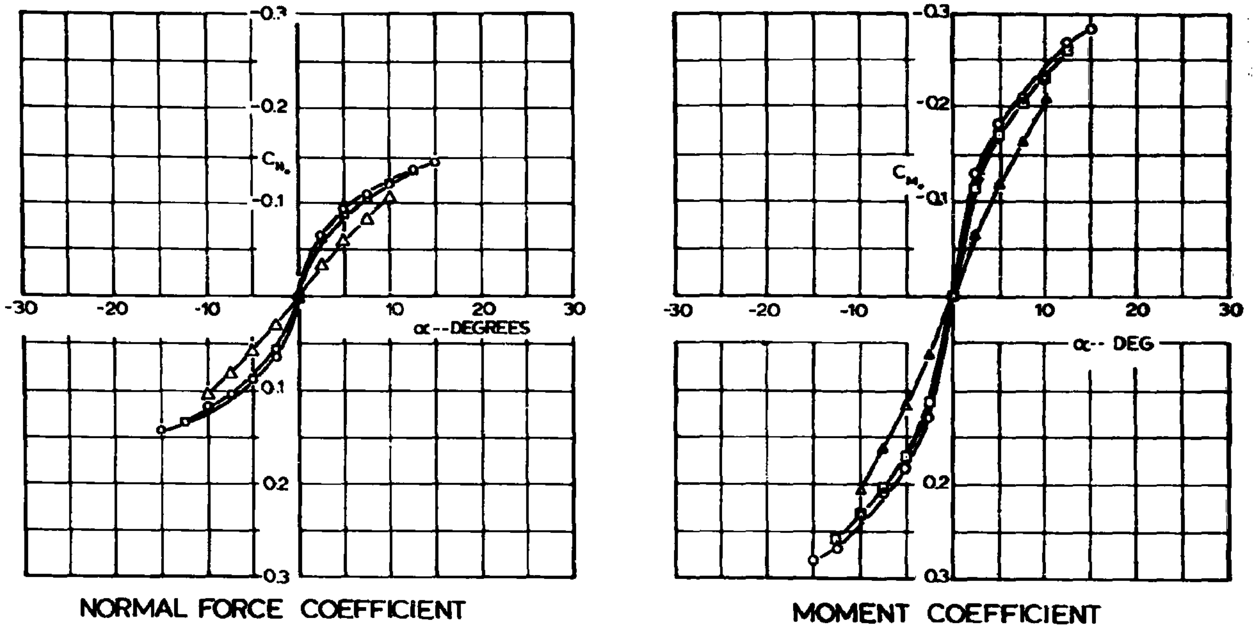


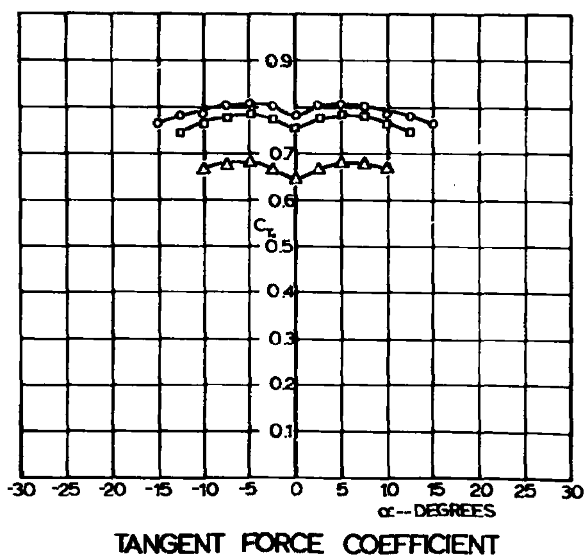




SYMBOL	NOMINAL POROSITY
○	9-11
□	60-90
△	120
▽	194

FIG-8 AERODYNAMIC COEFFICIENTS vs ANGLE OF ATTACK FOR CROSS TYPE PARACHUTES OF VARIOUS NOMINAL POROSITIES (W/L=.264, GEOMETRIC POROSITY 41.7%)
BASED ON S_o AND REYNOLDS NO. ≅ 4.5×10^5





SYMBOL	NOMINAL POROSITY
o	9-11
□	60-90
Δ	120

FIG-9 AERODYNAMIC COEFFICIENTS vs ANGLE OF ATTACK FOR CROSS TYPE PARACHUTES OF VARIOUS NOMINAL POROSITIES (W/L=.194, GEOMETRIC POROSITY 55.3%)

BASED ON S_o AND REYNOLDS NO. ≅ 4.5×10^5

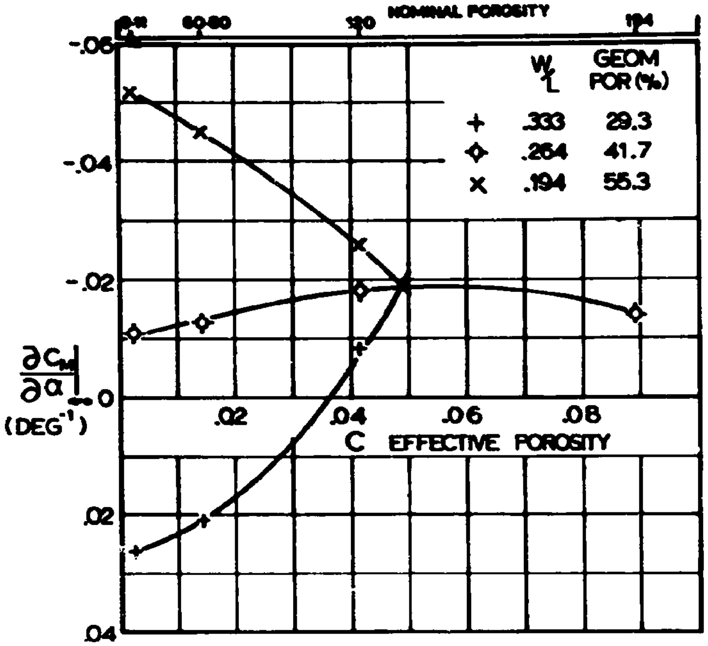


FIG 10. SLOPE OF MOMENT COEFFICIENT CURVE AT ZERO ANGLE OF ATTACK AS A FUNCTION OF EFFECTIVE POROSITY AT VARIOUS W/L VALUES

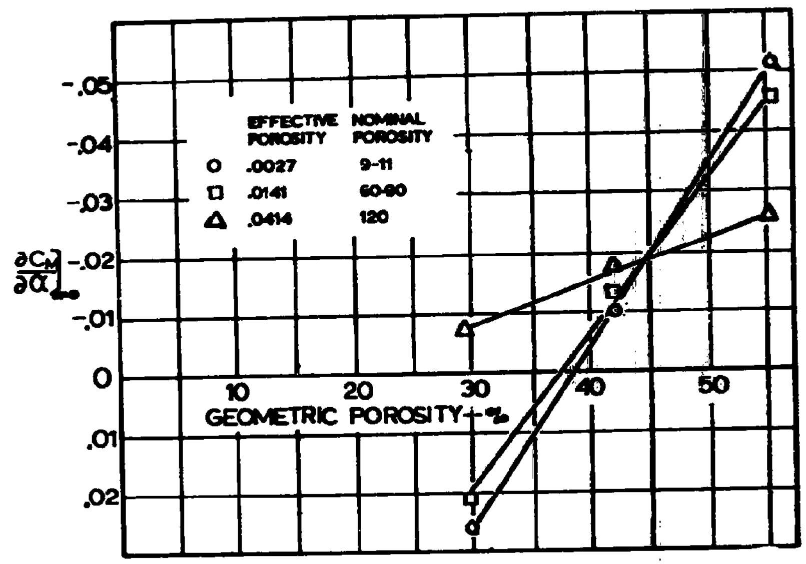


FIG 11. SLOPE OF MOMENT COEFICIENT CURVE AT ZERO ANGLE OF ATTACK AS A FUNCTION OF GEOMETRIC POROSITY FOR CROSS PARACHUTES AT VARIOUS EFFECTIVE POROSITIES

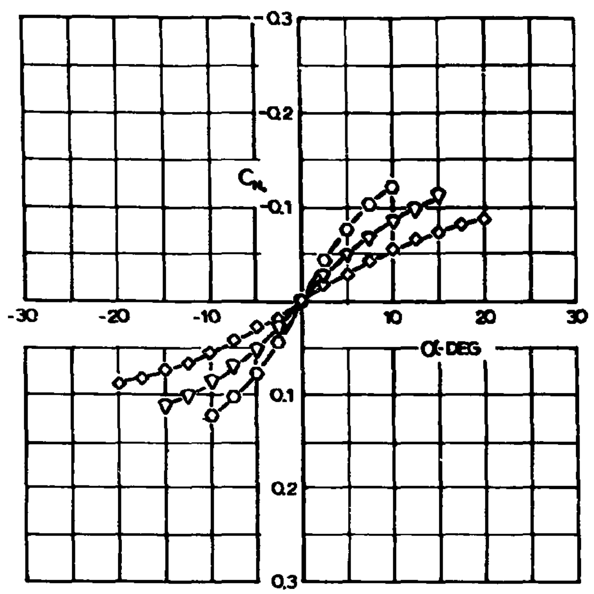
TABLE 2. STABILITY AND DRAG CHARACTERISTICS OF CROSS PARACHUTES IN FREE STREAM

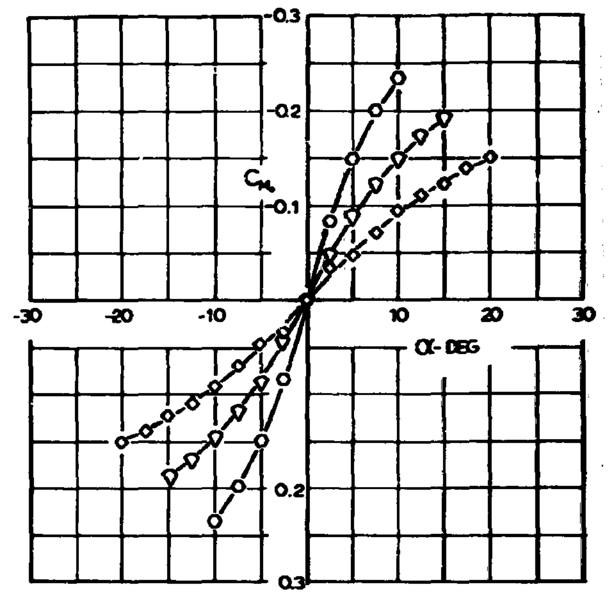
$\frac{W}{L}$	Nominal Porosity	Geometric Porosity	Effective Porosity C	α_{stable} (degrees)	$C_{T\alpha}$ stable	$\left.\frac{dC_M}{d\alpha}\right]_{\alpha=0}$ deg^{-1}
FREE STREAM						
.333	9 - 11	29.3%	.0027	± 16°	.86	+ .026
.333	60 - 90	29.3%	.0141	± 13°	.83	+ .021
.333	120	29.3%	.0414	0	.75	- .008
.264	9 - 11	41.7%	.0027	0	.84	- .011
.264	60 - 90	41.7%	.0141	0	.79	- .013
.264	120	41.7%	.0414	0	.67	- .018
.264	194	41.7%	.0893	0	.67	- .014
.194	9 - 11	55.3%	.0027	0	.78	- .052
.194	60 - 90	55.3%	.0141	0	.76	- .045
.194	120	55.3%	.0414	0	.64	- .026

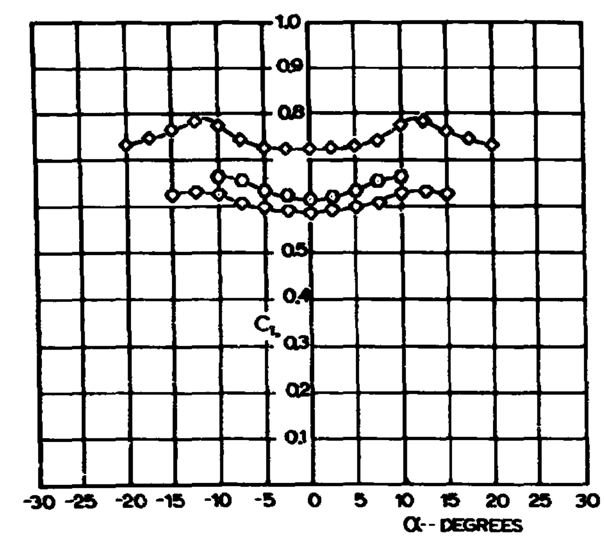
B. Aerodynamic Characteristics of the Cross Parachute in the Wake of the A-21 Cargo Container

As a result of stability and drag considerations, three parachutes were chosen for investigation in the wake of A-21 cargo container models. They are W/L = 0.264 with nominal porosities of 60 - 90 and 194 ft^3/ft^2-min, and W/L = .194 with a nominal porosity of 60 - 90 ft^3/ft^2-min.

Each of these parachutes was tested with each of the forebody - riser length combinations discussed previously. The aerodynamic coefficients are presented as a function of angle of attack in Figs 12, 13 and 14, each figure representing a different forebody - riser length combination. In general,



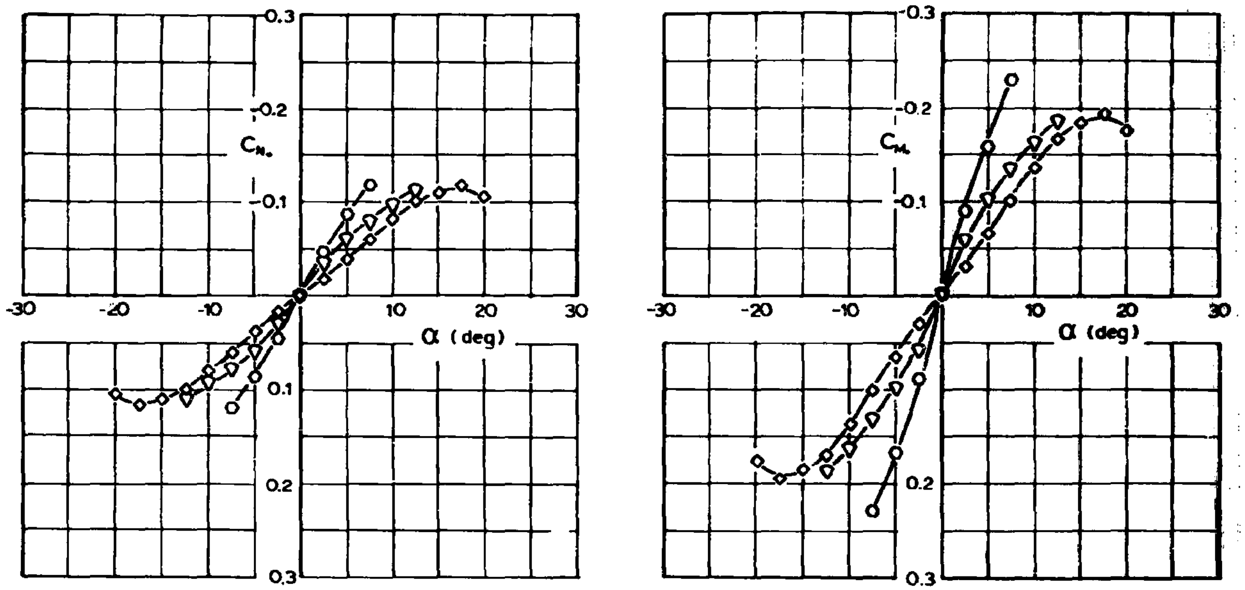


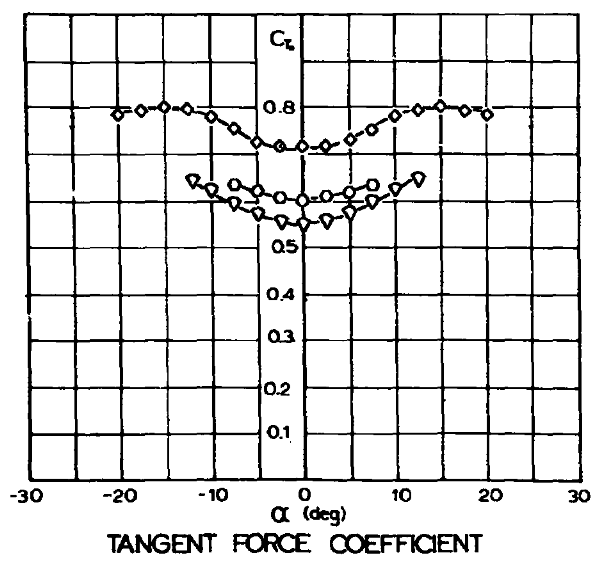


SYMBOL	W/L	NOMINAL POROSITY	A/S_o	EFFECTIVE POROSITY
○	.194	60-90	.146	.0141
◇	.264	60-90	.112	.0141
◇	.264	194	.112	.0893

FIG 12 AERODYNAMIC COEFFICIENTS vs ANGLE OF ATTACK FOR CROSS PARACHUTES WITH A-21 FOREBODY; (b/L=.278 AND RISER LENGTH=.80L)

BASED ON S_o AND REYNOLDS NO. = 4.5×10^5

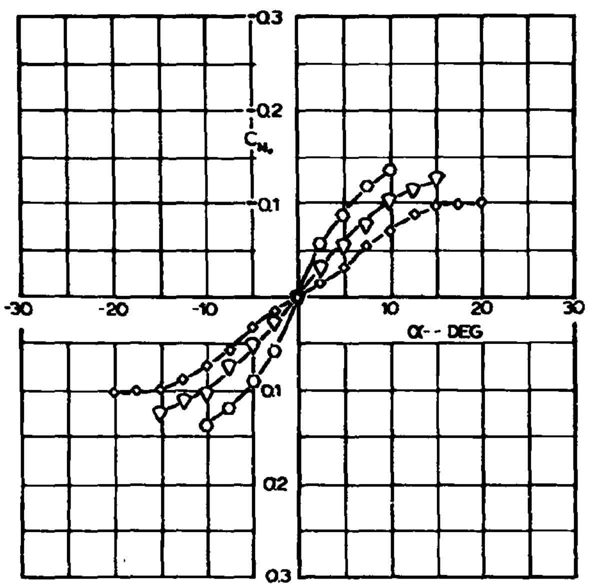




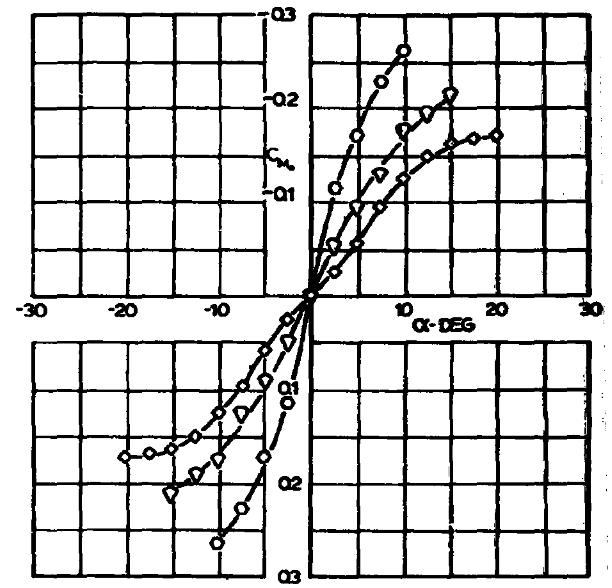
SYMBOL	W/L	NOMINAL POROSITY	A/S_o	EFFECTIVE POROSITY
O	.194	60-90	.146	.0141
◇	.264	60-90	.112	.0141
o	.264	194	.112	.0893

FIG 13 AERODYNAMIC COEFFICIENTS vs ANGLE OF ATTACK FOR CROSS PARACHUTES WITH A-21' FOREBODY, (b/L=.278 AND RISER LENGTH=.14L)

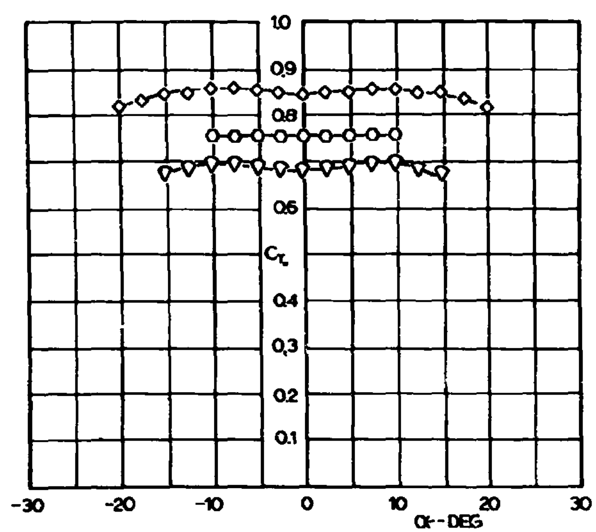
BASED ON S_o AND REYNOLDS NO ≅ 4.5×10^5



NORMAL FORCE COEFFICIENT



MOMENT COEFFICIENT



TANGENT FORCE COEFFICIENT

SYMBOL	W/L	NOMINAL POROSITY	A/S_o	EFFECTIVE POROSITY
O	194	60 - 90	.024	.0141
◇	264	60 - 90	.018	.0141
◇	264	194	.018	.0893

FIG 14 AERODYNAMIC COEFFICIENTS vs ANGLE OF ATTACK FOR CROSS PARACHUTES WITH A-21 FOREBODY (b/L=.112 AND RISER LENGTH=.08 L)
BASED ON S_o AND REYNOLDS NO. = 4.5×10^5

the stability of the parachute is changed only slightly by the presence of a forebody. For the forebody configuration with b/L = .278, little change is noted as the riser length is varied from .80L to .14L. Also, little stability change is noted as the relative size of the forebody is reduced from b/L = .278 to b/L = .112. The tangent force coefficients of the parachutes decrease significantly for all three parachutes in the region of $\alpha = 0°$ for the forebody tests with b/L = .278. However, for the forebody tests with b/L = .112, tangent force coefficients vary little from free stream values. Significant results of the wake studies are summarized in Table 3. The aerodynamic coefficients from the free stream and wake studies are tabulated in the appendix.

TABLE 3. STABILITY AND DRAG CHARACTERISTICS OF CROSS PARACHUTE WITH A-21 FOREBODY

$\frac{W}{L}$	Nominal Porosity	Geom. Por. %	Effective Porosity C	$\frac{A}{S_o}$	α_{stable} (Degrees)	$C_{T\alpha}$ stable	$\left.\frac{dC_M}{d\alpha}\right]_{\alpha=0}$ deg^{-1}
b/L = .278; .80 L Riser							
.194	60 - 90	55.3	.0141	.146	0	.62	- .034
.264	60 - 90	41.7	.0141	.112	0	.72	- .014
.264	194	41.7	.0839	.112	0	.59	- .018
b/L = .278, .14 L Riser							
.194	60 - 90	55.3	.0141	.146	0	.62	- .035
.264	60 - 90	41.7	.0141	.112	0	.72	- .012
.264	194	41.7	.0839	.112	0	.59	- .023
b/L = .112, .06 L Riser							
.194	60 - 90	55.3	.0141	.024	0	.76	- .045
.264	60 - 90	41.7	.0141	.018	0	.83	- .010
.264	194	41.7	.0839	.018	0	.67	- .020

C. <u>Comparison of Full Scale and Model Tests</u>

Full scale drop tests on the Cross parachute have been conducted by government agencies to evaluate this type of parachute.

The U. S. Air Force has conducted a drop test program (Ref 5) using a 13.6 ft nominal diameter parachute with loads ranging from approximately 75 lbs to 232 lbs. In these tests the measured drag coefficient varied from 0.69 to 0.44 with a canopy loading of .52 lb/ft^2 to 1.60 lb/ft^2, respectively.

A direct comparison of this data with the wind tunnel model data is not readily possible, since several characteristics of the full scale system are not known. The cloth porosity of the canopy and the dimensions of the load, two parameters which will directly influence the drag coefficient, are not specified.

However, in general, it appears that the values of drag coefficient measured in the wind tunnel are somewhat higher than those experienced in these full scale tests.

Limited test results obtained from the U. S. Army Quartermaster Corps, Natick, Massachusetts, indicate a drag coefficient for a 16 ft nominal diameter Cross parachute to be in the order of 0.55. These studies were conducted with canopy loads producing an equilibrium velocity of 130 ft/sec, approximately double the highest velocity recorded in Ref 5 above. Again, certain pertinent canopy characteristics and loading information was not specified.

It appears that with the generally observed increase in drag coefficient with decreasing canopy loads, the Army test data would agree with the wind tunnel data contained in this report. Unfortunately, it is still not known why the effective drag coefficient depends on the canopy loading.

The drag coefficient obtained from full scale tests, as well as those from the subsonic wind tunnel, are shown in Fig 15.

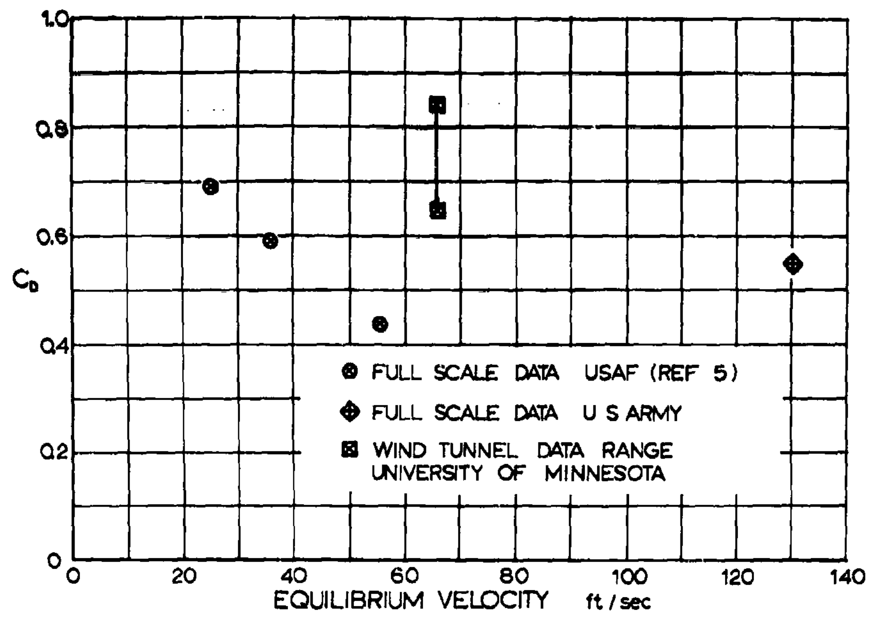


FIG 15. DRAG COEFFICIENT AS A FUNCTION OF EQUILIBRIUM VELOCITY FOR SEVERAL FULL SCALE AND WIND TUNNEL TESTS

It appears that a direct comparison of wind tunnel and full scale data cannot be made until all related circumstances are known.

Furthermore, the quoted wind tunnel data is strictly related to a zero angle of attack, whereas the exact angle of attack of the parachute in full size drop tests is not known.

Also, the drag coefficients extracted from full size tests are all obtained under conditions of the presence of a forebody. Since there is no information available on the forebody employed in the full size drop tests, one cannot really compare the two sets of data.

In summary, it is suggested that the presented wind tunnel data be considered as correct in order of magnitude, but that possibly of more importance is the relative relationship of the wind tunnel data results to each other.

4. SUMMARY

Ten Cross parachutes were studied in a wind tunnel program to fulfill the following objectives:

1) Establish the drag and stability characteristics of this type of parachute over a range of angle of attack
2) Determine the effect of canopy geometry and cloth porosity on these aerodynamic coefficients
3) Determine the effect of the presence of a wake producing body upstream on the aerodynamic coefficients.

The results show a general decline of tangent force with increased cloth porosity as is generally the case.

The general trend toward greater stability with increasing cloth porosity is noted for canopy configurations with less than about 44 per cent geometric porosity. However, above this value a reversal in the trend has been found.

Of all the configurations studied, only two appeared to be obviously undesirable from the standpoint of stability, and both are of the largest width to length ratio (W/L = 0.333). The low porosity model, 9 - 11 nominal porosity, has the greatest range of instability, $\pm$ 16° about zero angle of attack, and the medium porosity model, 60 - 90 nominal porosity, has an instability range of $\pm$ 13° about the zero angle of attack.

In the wake of an A-21 cargo container, the stability of the parachute remains at about its free stream value. The tangent force coefficient is reduced by an appreciable amount in the wake of the larger A-21 forebody, but essentially obtains its free stream value as the size of the container is decreased to b/L = .112.

With the exception of the unstable configurations, most models showed desirable parachute characteristics in the wind tunnel. The three models used for testing behind the A-21 container as a forebody were deemed to have had the best overall performance in singly suspended studies.

APPENDIX

AERODYNAMIC COEFFICIENTS OF CROSS PARACHUTES IN FREE STREAM AND IN THE WAKE OF AN A-21 CARGO CONTAINER

TABLE 4. AERODYNAMIC COEFFICIENTS OF CROSS PARACHUTES, W/L=.333

α	C_{T_o}	C_{N_o}	C_{M_o}
Nominal Porosity 9 - 11 ft^3/ft^2-min Effective Porosity .0027			
0	.86	0	0
$\pm$ 2½	.91	$\pm$ .04	$\pm$ .07
$\pm$ 5	.93	$\pm$ .04	$\pm$ .06
$\pm$ 7½	.93	$\pm$ .04	$\pm$ .06
$\pm$ 10	.95	$\pm$ .03	$\pm$ .04
$\pm$ 12½	.95	$\pm$ .02	$\pm$ .03
$\pm$ 15	.95	$\pm$ .01	$\pm$ .02
$\pm$ 17½	.94	$\mp$ .01	$\mp$ .01
$\pm$ 20	.94	$\mp$ .03	$\mp$ .04
$\pm$ 25	.93	$\mp$ .04	$\mp$ .06
$\pm$ 30	.92	$\mp$ .04	$\mp$ .06
Nominal Porosity 60 - 90 ft^3/ft^2-min Effective Porosity .0141			
0	.83	0	0
$\pm$ 2½	.87	$\pm$ .03	$\pm$ .05
$\pm$ 5	.90	$\pm$ .03	$\pm$ .05
$\pm$ 7½	.90	$\pm$ .02	$\pm$ .04
$\pm$ 10	.91	$\pm$ .01	$\pm$ .02
$\pm$ 12½	.90	$\pm$ .01	$\pm$ .01
$\pm$ 15	.90	$\mp$ .02	$\mp$ .03
$\pm$ 17½	.90	$\mp$ .03	$\mp$ .05
$\pm$ 20	.89	$\mp$ .04	$\mp$ .07
$\pm$ 25	.86	$\mp$ .06	$\mp$ .09
$\pm$ 30	.85	$\mp$ .05	$\mp$ .08
Nominal Porosity 120 ft^3/ft^2-min Effective Porosity .0414			
0	.75	0	0
$\pm$ 2½	.77	$\mp$ .01	$\mp$ .02
$\pm$ 5	.77	$\mp$ .03	$\mp$ .04
$\pm$ 7½	.77	$\mp$ .03	$\mp$ .05
$\pm$ 10	.78	$\mp$ .04	$\mp$ .06
$\pm$ 12½	.77	$\mp$ .05	$\mp$ .08
$\pm$ 15	.76	$\mp$ .06	$\mp$ .10
$\pm$ 17½	.75	$\mp$ .08	$\mp$ .12
$\pm$ 20	.74	$\mp$ .09	$\mp$ .14
$\pm$ 25	.70	$\mp$ .09	$\mp$ .14

TABLE 5. AERODYNAMIC COEFFICIENTS OF CROSS PARACHUTES WITH W/L=.264

α	C_{T_o}	C_{N_o}	C_{M_o}
Nominal Porosity 9 - 11 ft^3/ft^2-min Effective Porosity .0027			
0	.84	0	0
$\pm$ 2½	.89	$\mp$.02	$\mp$ .03
$\pm$ 5	.90	$\mp$.03	$\mp$ .05
$\pm$ 7½	.90	$\mp$.05	$\mp$ .08
$\pm$ 10	.90	$\mp$.07	$\mp$ .11
$\pm$ 12½	.89	$\mp$.08	$\mp$ .14
$\pm$ 15	.88	$\mp$.09	$\mp$ .15
$\pm$ 17½	.85	$\mp$.08	$\mp$ .14
$\pm$ 20	.84	$\mp$.08	$\mp$ .13
$\pm$ 25	.82	$\mp$.06	$\mp$ .10
Nominal Porosity 60 - 90 ft^3/ft^2-min Effective Porosity .0141			
0	.79	0	0
$\pm$ 2½	.84	$\mp$.02	$\mp$ .03
$\pm$ 5	.86	$\mp$.03	$\mp$ .05
$\pm$ 7½	.86	$\mp$.04	$\mp$ .07
$\pm$ 10	.87	$\mp$.05	$\mp$ .09
$\pm$ 12½	.86	$\mp$.06	$\mp$ .10
$\pm$ 15	.85	$\mp$.07	$\mp$ .12
$\pm$ 17½	.83	$\mp$.08	$\mp$ .13
$\pm$ 20	.82	$\mp$.09	$\mp$ .14
Nominal Porosity 120 ft^3/ft^2-min Effective Porosity .0414			
0	.67	0	0
$\pm$ 2½	.72	$\mp$.03	$\mp$ .04
$\pm$ 5	.74	$\mp$.05	$\mp$ .08
$\pm$ 7½	.72	$\mp$.06	$\mp$ .11
$\pm$ 10	.72	$\mp$.08	$\mp$ .14
$\pm$ 12½	.71	$\mp$.10	$\mp$ .17
$\pm$ 15	.70	$\mp$.12	$\mp$ .20
$\pm$ 17½	.68	$\mp$.13	$\mp$ .23
Nominal Porosity 194 ft^3/ft^2-min Effective Porosity .0893			
0	.67	0	0
$\pm$ 2½	.68	$\mp$.02	$\mp$ .03
$\pm$ 5	.69	$\mp$.04	$\mp$ .07
$\pm$ 7½	.69	$\mp$.06	$\mp$ .10
$\pm$ 10	.69	$\mp$.08	$\mp$ .13
$\pm$ 12½	.68	$\mp$.09	$\mp$ .16
$\pm$ 15	.68	$\mp$.11	$\mp$ .18

TABLE 6. AERODYNAMIC COEFFICIENTS OF CROSS PARACHUTES WITH W/L=.194

α	C_{T_o}	C_{N_o}	C_{M_o}
Nominal Porosity 9 - 11 ft^3/ft^2-min Effective Porosity .0027			
0	.78	0	0
$\pm$ 2½	.80	$\mp$ .07	$\mp$ .13
$\pm$ 5	.81	$\mp$ .09	$\mp$ .18
$\pm$ 7½	.80	$\mp$ .11	$\mp$ .21
$\pm$ 10	.78	$\mp$ .12	$\mp$ .23
$\pm$ 12½	.79	$\mp$ .14	$\mp$ .26
$\pm$ 15	.76	$\mp$ .14	$\mp$ .28
Nominal Porosity 60 - 90 ft^3/ft^2-min Effective Porosity .0141			
0	.76	0	0
$\pm$ 2½	.78	$\mp$.06	$\mp$ .11
$\pm$ 5	.78	$\mp$.09	$\mp$ .17
$\pm$ 7½	.78	$\mp$.11	$\mp$ .21
$\pm$ 10	.77	$\mp$.12	$\mp$ .23
$\pm$ 12½	.75	$\mp$.13	$\mp$ .26
Nominal Porosity 120 ft^3/ft^2-min Effective Porosity .0414			
0	.64	0	0
$\pm$ 2½	.67	$\mp$ .03	$\mp$ .06
$\pm$ 5	.68	$\mp$ .06	$\mp$ .12
$\pm$ 7½	.67	$\mp$ .08	$\mp$ .16
$\pm$ 10	.66	$\mp$ .11	$\mp$ .21

TABLE 7. AERODYNAMIC COEFFICIENTS FOR CROSS PARACHUTES WITH A-21 FOREBODY b/L=.278 AND .80L RISER

α	C_{T_o}	C_{N_o}	C_{M_o}
W/L = .194 Nom. Pos. 60-90 ft^3/ft^2-min			
0	.61	0	0
± 2½	.62	∓ .04	∓ .09
± 5	.64	∓ .08	∓ .15
± 7½	.65	∓ .10	∓ .20
± 10	.66	∓ .12	∓ .24
W/L = .264 Nom. Pos. 60-90 ft^3/ft^2-min			
0	.72	0	0
± 2½	.72	∓ .02	∓ .03
± 5	.72	∓ .03	∓ .05
± 7½	.74	∓ .04	∓ .07
± 10	.78	∓ .06	∓ .09
± 12½	.78	∓ .07	∓ .11
± 15	.76	∓ .07	∓ .12
± 17½	.75	∓ .08	∓ .14
± 20	.75	∓ .09	∓ .15
W/L = .264 Nom. Pos. 194 ft^3/ft^2-min			
0	.59	0	0
± 2½	.59	∓ .03	∓ .04
± 5	.60	∓ .05	∓ .09
± 7½	.61	∓ .07	∓ .12
± 10	.63	∓ .09	∓ .15
± 12½	.63	∓ .10	∓ .17
± 15	.62	∓ .11	∓ .19

TABLE 8. AERODYNAMIC COEFFICIENTS FOR CROSS PARACHUTES WITH A-21 FOREBODY, b/L=.278 AND .14L RISER

α	C_{T_o}	C_{N_o}	C_{M_o}
W/L = .194 Nom. Pos. 60-90 ft^3/ft^2-min			
0	.60	0	0
± 2½	.60	∓ .05	∓ .09
± 5	.62	∓ .09	∓ .17
± 7½	.64	∓ .12	∓ .23
W/L = .264 Nom. Pos. 60-90 ft^3/ft^2-min			
0	.72	0	0
± 2½	.72	∓ .02	∓ .03
± 5	.73	∓ .04	∓ .07
± 7½	.75	∓ .06	∓ .10
± 10	.78	∓ .08	∓ .14
± 12½	.80	∓ .10	∓ .17
± 15	.80	∓ .11	∓ .18
± 17½	.80	∓ .12	∓ .20
± 20	.79	∓ .11	∓ .18
W/L = .264 Nom. Pos. 194 ft^3/ft^2-min			
0	.55	0	0
± 2½	.56	∓ .03	∓ .06
± 5	.57	∓ .07	∓ .10
± 7½	.60	∓ .08	∓ .14
± 10	.63	∓ .10	∓ .16
± 12½	.64	∓ .11	∓ .19

TABLE 9. AERODYNAMIC COEFFICIENTS FOR CROSS PARACHUTES WITH A-21 FOREBODY, b/L=.112 AND .06L RISER

α	C_{T_o}	C_{N_o}	C_{M_o}
W/L = .194 Nom. Pos. 60-90 ft^3/ft^2-min			
0	.76	0	0
± 2½	.75	∓ .06	∓ .11
± 5	.76	∓ .09	∓ .17
± 7½	.75	∓ .12	∓ .23
± 10	.75	∓ .14	∓ .26
W/L = .264 Nom. Pos. 60-90 ft^3/ft^2-min			
0	.83	0	0
± 2½	.85	∓ .02	∓ .02
± 5	.86	∓ .03	∓ .06
± 7½	.86	∓ .06	∓ .10
± 10	.86	∓ .07	∓ .12
± 12½	.85	∓ .09	∓ .15
± 15	.84	∓ .10	∓ .16
± 17½	.84	∓ .10	∓ .17
± 20	.82	∓ .10	∓ .17
W/L = .264 Nom. Pos. 194 ft^3/ft^2-min			
0	.67	0	0
± 2½	.68	∓ .03	∓ .05
± 5	.69	∓ .05	∓ .09
± 7½	.70	∓ .08	∓ .13
± 10	.70	∓ .10	∓ .18
± 12½	.69	∓ .11	∓ .19
± 15	.67	∓ .12	∓ .21

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13. ABSTRACT

Wind tunnel studies have been performed on several configurations of the Cross parachute. Both the canopy geometry and the cloth porosity have been varied to provide data over the entire range for which the canopy may be used. In addition, the performance of these canopies in the wake of a forebody has been evaluated.

This report contains the results of three-component studies on these models as well as a discussion of the canopy performance in light of the tests performed.

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